Weighting-Like Diagnostics for Nonlinear Bayesian Hierarchical Models

Ryan Giordano, Alice Cima, Erin Hartman, Jared Murray, Avi Feller

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Are US non-voters becoming more Republican?

Blue Rose research says yes:

“Politically disengaged voters have become much more Republican, and because less-engaged voters swung away from [Democrats], an expanded electorate meant a more Republican electorate.”

(Blue Rose Research 2024)
(major professional pollsters)

On Data and Democracy **says no:**

“Claims of a decisive pro-Republican shift among the overall non-voting population are not supported by the most reliable, large-scale post-election data currently available.”

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- The problem is very hard (it’s difficult to accurately poll non–voters)
- Different data sources
- ⋆⋆⋆ **Different statistical methods**
  - Blue Rose uses Bayesian hierarchical modeling (MrP)
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Our contribution

We define "MrP local equivalent weights" (MrPlew) that:

- Are easily computable from MCMC draws and standard software, and
- Provide MrP versions of key weighting estimator diagnostics.

$\Rightarrow$ **MrPlew provides direct comparisons between MrP and calibration weighting.**

Outline

- Introduce the statisical problem
  - Contrast calibration weighting and MrP
  - Prior work: Equivalent weights for linear models
  - Equivalent weights and implicit weights for non–linear models
  - Our task: Rigorously justify using locally equivalent weights for diagnostics

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- Locally equivalent weights for covariate balance
  - Describe classical covariate balance
  - Introduce a MrPlew "local empirical consistency check"
  - Theoretical support
  - Examples of real-world results

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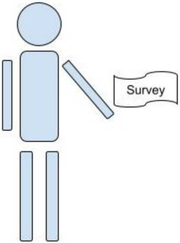
- Other directions
  - High–level restatement of the logic of our procedure
  - Local versions of other common diagnostics for linear estimators
  - Ongoing and future work

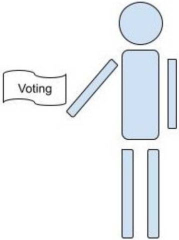
The basic problem

We have a survey population, for whom we observe:

- Covariates $\mathbf{x}$ (e.g. race, gender, zip code, age, education level)
- Responses y (e.g. A binary response to “do you support Trump”)

We want the average response in a target population, in which we observe only covariates.





Observe $(\mathbf{x}_i, y_i)$ for $i = 1, \ldots, N_S$ | Observe $\mathbf{x}_j$ for $j = 1, \ldots, N_T$

[1]Photo copyright: Mark Taylor / `naturepl.com`

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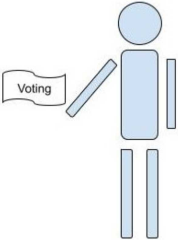

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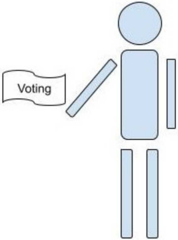

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How can we use the covariates to say something about the target responses?

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Two approaches

We want $\mu := \frac{1}{N_T} \sum_{j=1}^{N_T} y_j$, but don't observe target y_j. Let $Y_{\mathcal{S}} = \{y_1, \dots, y_{N_S}\}$.

- Assume $p(y|\mathbf{x})$ is the same in both populations,
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Calibration weighting

▶ Choose "calibration weights" w_i
using only the regressors $\mathbf{x}$
(e.g. raking weights)

Bayesian hierarchical modeling (MrP)

▶ Choose $\mathbb{E}\left[y|\mathbf{x},\theta\right] = m(\theta^{\intercal}\mathbf{x})$,
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- Weights give interpretable diagnostics:
  - Frequentist variability
  - Regressor balance
  - Partial pooling

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$\leftarrow$ Today, we'll open the box and provide MrP analogues of all these diagnostics

Prior work: Equivalent weights for linear models

Gelman (2007b) observes that MrP is a weighting estimator when $\hat{y}$ is computed with OLS:

$$\hat{\mu}^{\text{MrP}}(Y_{\mathcal{S}}) = \frac{1}{N_T}\sum_{j=1}^{N_T}\hat{y}_j = \frac{1}{N_T}\sum_{j=1}^{N_T}\underbrace{\mathbf{x}_j^{\intercal}\hat{\theta}}_{\text{Linear in } Y_{\mathcal{S}}}$$

Most existing literature on comparing weighting and MrP focus on such linear models. [2]

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But what if you use a non–linear link function? Or a hierarchical model?

> *"It would also be desirable to use nonlinear methods ... but then it would seem difficult to construct even approximately equivalent weights. Weighting and fully nonlinear models would seem to be completely incompatible methods."* — *(Gelman 2007a)*

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Approximately equivalent weights for (some) logistic regression MrP

- Suppose the model is $m(\mathbf{x}^\intercal \theta) = \mathrm{Logistic}(\mathbf{x}^\intercal \theta)$, with MLE $\hat{\theta}$.
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The map from $Y_{\mathcal{S}} \mapsto m(\mathbf{x}_j^\intercal \hat{\theta})$ is *inherently nonlinear*.

But *some sample averages* of $m(\mathbf{x}_j^\intercal \hat{\theta})$ can be approximately linear.

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Example

Suppose $\frac{\mathcal{P}_T(\mathbf{x})}{\mathcal{P}_S(\mathbf{x})} \approx \alpha^\intercal \mathbf{x}$ for some α. **Then MrP is a *approximately* a CW estimator.**

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But what are the weights? We don't observe $\frac{\mathcal{P}_T(\mathbf{x})}{\mathcal{P}_S(\mathbf{x})}$, so can't estimate α directly.

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$$\hat{\mu}^{\mathrm{MrP}}(Y_{\mathcal{S}}) = \frac{1}{N_T} \sum_{j=1}^{N_T} m(\mathbf{x}_j^\intercal \hat{\theta}) = \frac{1}{N_S} \sum_{i=1}^{N_S} \underbrace{w_i^{\mathrm{MrP}}}_{\alpha^\intercal \mathbf{x}_i} y_i + \text{Small error}$$

Key idea (informal)

If $\hat{\mu}^{\mathrm{MrP}}(Y_{\mathcal{S}})$ is approximately linear, then[3] $w_i^{\mathrm{MrP}} \approx N_S \frac{\partial \hat{\mu}^{\mathrm{MrP}}(Y_{\mathcal{S}})}{\partial y_i}$.

[3] For MLEs, $\frac{\partial \hat{\mu}^{\mathrm{MrP}}(Y_{\mathcal{S}})}{\partial y_i}$ is given by the implicit function theorem. (Krantz and Parks 2012; **G.**, Stephenson, et al. 2019)

Approximately equivalent weights for (some) logistic regression MrP

- Suppose the model is $m(\mathbf{x}^\intercal \theta) = \mathrm{Logistic}(\mathbf{x}^\intercal \theta)$, with MLE $\hat{\theta}$.
- MrP is $\hat{\mu}^{\mathrm{MrP}}(Y_{\mathcal{S}}) = \frac{1}{N_T} \sum_{j=1}^{N_T} m(\mathbf{x}_j^\intercal \hat{\theta})$.

Example

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Note: The derivatives w_i^{MrP} now have two potentially distinct interpretations:

- **Equivalent weights:** A characterization of $Y_{\mathcal{S}} \mapsto \hat{\mu}^{\mathrm{MrP}}(Y_{\mathcal{S}})$ for diagnostics
- **Implicit weights:** An estimate of $\mathcal{P}_T(\mathbf{x}) / \mathcal{P}_S(\mathbf{x})$

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Local weights for nonlinear hierarchical logistic regression MrP

- Suppose the model is $m(\mathbf{x}^\intercal \theta) = \mathrm{Logistic}(\mathbf{x}^\intercal \theta)$.
- Set a hierarchical prior $\mathcal{P}(\theta|\Sigma)\mathcal{P}(\Sigma)$, use MCMC to draw from $\mathcal{P}(\theta|\text{Survey data})$.
- MrP is $\hat{\mu}^{\text{MrP}}(Y_{\mathcal{S}}) = \frac{1}{N_T} \sum_{j=1}^{N_T} \mathbb{E}_{\mathcal{P}(\theta|\text{Survey data})} \left[m(\mathbf{x}_j^\intercal \theta) \right]$.

No reason to think $Y_{\mathcal{S}} \mapsto \hat{\mu}^{\text{MrP}}(Y_{\mathcal{S}})$ is even approximately **globally** linear.

---

[4] Diaconis and Freedman 1986; Gustafson 1996; Efron 2015; **G.**, Broderick, and Jordan 2018.

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No reason to think $Y_{\mathcal{S}} \mapsto \hat{\mu}^{\mathrm{MrP}}(Y_{\mathcal{S}})$ is even approximately **globally** linear.

But can still compute and analyze $w_i^{\mathrm{MrP}} := N_S \frac{\partial \hat{\mu}^{\mathrm{MrP}}(Y_{\mathcal{S}})}{\partial y_i}$ using Bayesian sensitivity analysis![4]

MrP weights for MCMC

$$w_i^{\mathrm{MrP}} := N_S \frac{\partial \hat{\mu}^{\mathrm{MrP}}(Y_{\mathcal{S}})}{\partial y_i} = N_S \frac{1}{N_T} \sum_{j=1}^{N_T} \underbrace{\mathrm{Cov}_{\mathcal{P}(\theta|\text{Survey data})}\left(m(\mathbf{x}_j^\intercal \theta), \theta^\intercal \mathbf{x}_i\right)}_{\text{Can estimate without rerunning MCMC!}}$$

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The derivatives w_i^{MrP} *again* have two potentially distinct interpretations:

- **Locally equivalent weights:** A characterization of $Y_{\mathcal{S}} \mapsto \hat{\mu}^{\mathrm{MrP}}(Y_{\mathcal{S}})$ for diagnostics
- **Locally implicit weights:** An estimate of $\mathcal{P}_T(\mathbf{x})/\mathcal{P}_S(\mathbf{x})$

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This talk will focus only on locally equivalent weights. (Implicit weights is ongoing work!)

[4] Diaconis and Freedman 1986; Gustafson 1996; Efron 2015; **G.**, Broderick, and Jordan 2018.

Locally equivalent weights for hierarchical logistic regression MrP

- Suppose the model is $m(\mathbf{x}^\intercal\theta) = \text{Logistic}(\mathbf{x}^\intercal\theta)$.
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MrP locally equivalent weights (MrPlew)

For new data $\tilde{Y}_{\mathcal{S}}$, form a **MrP locally equivalent weighting**:

$$\hat{\mu}^{\text{MrP}}(\tilde{Y}_{\mathcal{S}}) \approx \hat{\mu}^{\text{MrP}}(Y_{\mathcal{S}}) + \sum_{i=1}^{N_{\mathcal{S}}} w_i^{\text{MrP}}(\tilde{y}_i - y_i)$$

Our task is to rigorously show that even such local weights can be meaningfully used diagnostically in the same ways we use global weights.

Real Data: Marital Name Change Survey

Analysis of changing names after marriage[5].

- **Target population:** ACS survey of US population 2017–2022[6]
- **Survey population:** Marital Name Change Survey (from Twitter)[7]
- **Respose:** Did the female partner keep their name after marriage?
- For regressors, use bins of age, education, state, and decade married.

Survey observations: $N_S = 4,364$

Target observations (rows): $N_T = 4,085,282$

Uncorrected survey mean: $\frac{1}{N_S}\sum_{i=1}^{N_S} y_i = 0.462$

Raking: $\hat{\mu}^{\mathrm{WGT}}(Y_{\mathcal{S}}) = 0.263$

MrP: $\hat{\mu}^{\mathrm{MrP}}(Y_{\mathcal{S}}) = 0.288 \quad (\text{Post. sd} = 0.0169)$

[5] Based on Alexander (2019).

[6] Ruggles et al. 2024.

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The weights can look very different!

Does this mean anything?

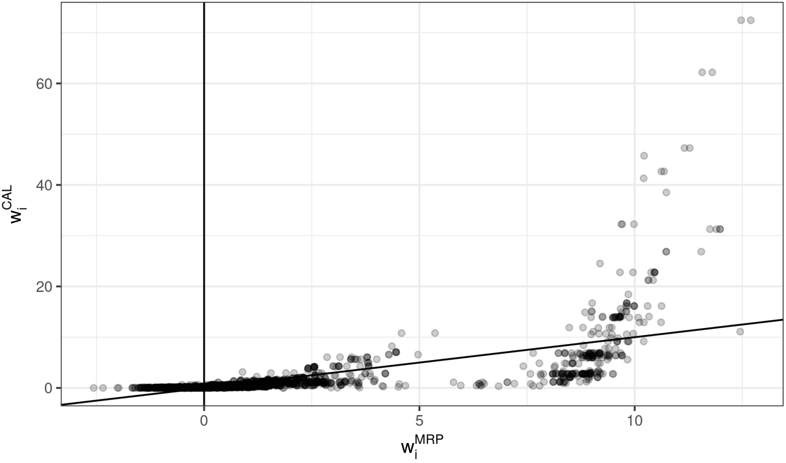

Figure 1: Comparison between raking and MrPlew weights for the Name Change dataset

The weights can look very different!

Does this mean anything?

Does the spread relate to frequentist variance?

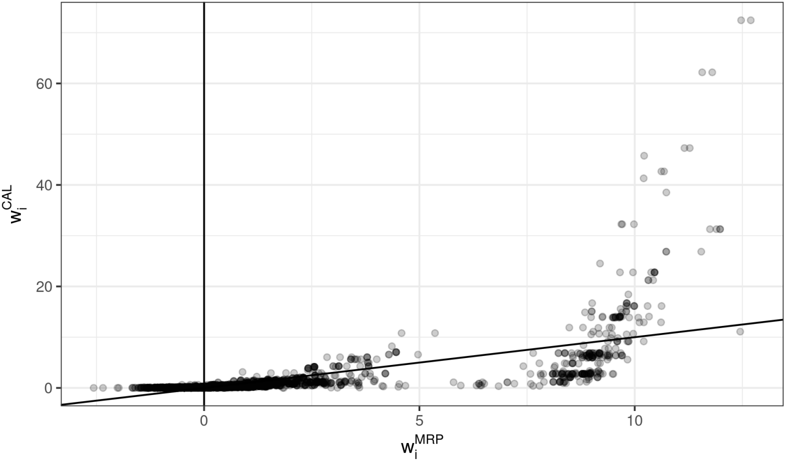

Figure 1: Comparison between raking and MrPlew weights for the Name Change dataset

Frequentist variance estimation

Let $\hat{\text{Var}}(\cdot)$ denote the sample variance.

Calibration weighting standard errors sketch: [8]

If we have $\hat{\mu}^{\text{WGT}}(Y_{\mathcal{S}}) = \frac{1}{N_S} \sum_{i=1}^{N_S} w_i y_i$ and a consistent residual estimate ε_i, then

$$\hat{\text{Var}}(w_i \varepsilon_i) \approx \text{Var}\left(\sqrt{N_S}\hat{\mu}^{\text{WGT}}(Y_{\mathcal{S}})\right).$$

[8] E.g. , Deville, Särndal, and Sautory (1993) and Fuller (2011).

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MrPlew Standard error consistency theorem sketch (Our contribution): [9]

For Bayesian hierarchical logictic regression, define $\varepsilon_i = y_i - \mathbb{E}_{\mathcal{P}(\theta|\text{Survey data})}\left[m(\mathbf{x}_i^\intercal\theta)\right]$.

We state mild conditions under which, as $N_S \to \infty$, for some μ_∞ and variance V,

$$\sqrt{N_S}\left(\hat{\mu}^{\text{MrP}}(Y_{\mathcal{S}}) - \mu_\infty\right) \to \mathcal{N}(0, V) \quad \text{and}$$
$$\hat{\text{Var}}\left(w_i^{\text{MrP}}\varepsilon_i\right) \to V.$$

The use of w_i^{MrP} is analogous to the use of w_i for frequentist variance estimation.

[8] E.g. , Deville, Särndal, and Sautory (1993) and Fuller (2011).

[9] This is essentially a corollary of our earlier work on the Bayesian infinitesimal jackknife. (**G.** and Broderick 2024)

Standard error estimation

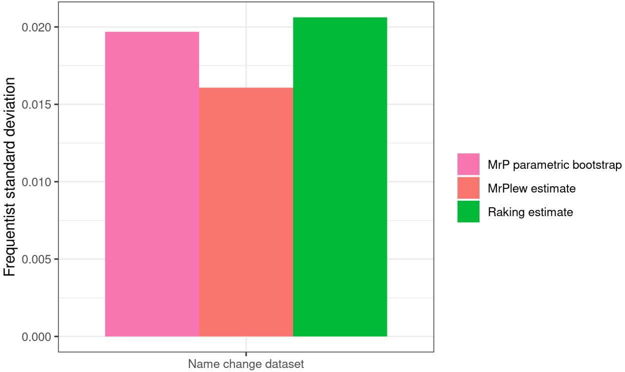

Figure 2: Frequentist standard deviation estimates

Standard error estimation

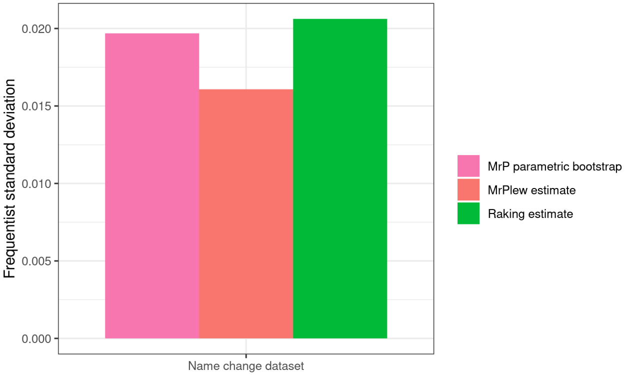

Figure 2: Frequentist standard deviation estimates

Running fifty MCMC parametric bootstraps: ≈ 79 hours

Computing approximate weights: 16 seconds

Other uses

Does this mean anything?

Yes: The “spread” relates to frequentist variance just as in weighting estimators.

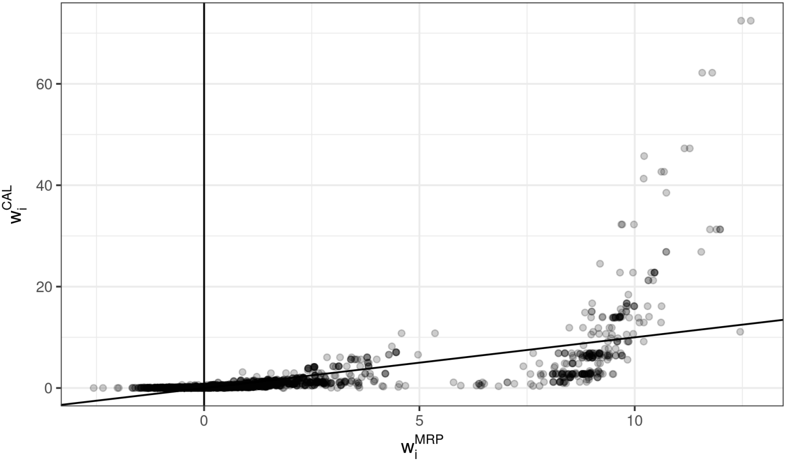

Figure 3: Comparison between raking and MrPlew weights for the Name Change dataset

Does this mean anything?

Yes: The "spread" relates to frequentist variance just as in weighting estimators.

What about covariate balance?

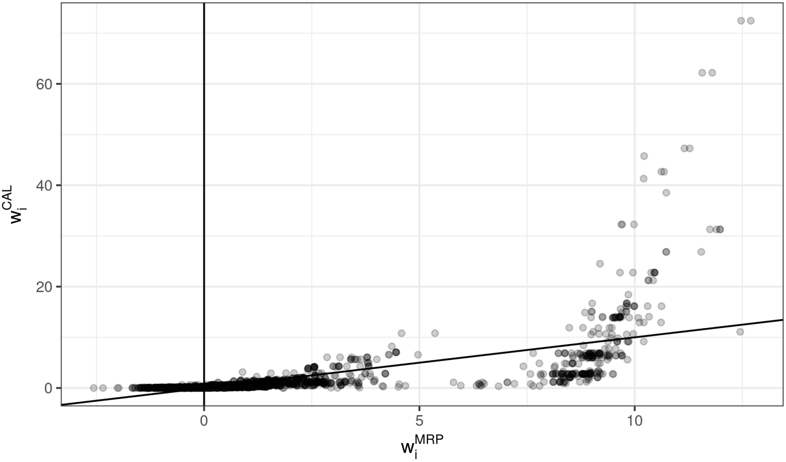

Figure 3: Comparison between raking and MrPlew weights for the Name Change dataset

Extra slides

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Real Data: Lax Philips

Analysis of national support for gay marriage.[10]

- **Target population:** US Census Public Use Microdata Sample 2000
- **Survey population:** Combined national-level polls from 2004
- **Respose:** "Do you favor allowing gay and lesbian couples to marry legally?"
- For regressors, use race, gender, age, education, state, region, and continuous statewide religion and political characteristics, including some analyst–selected interactions.

Survey observations: $N_S = 6,341$

Target observations (rows): $N_T = 9,694,541$

Uncorrected survey mean: $\frac{1}{N_S} \sum_{i=1}^{N_S} y_i = 0.333$

Raking: $\hat{\mu}_{\text{WGT}} = 0.33$

MrP: $\hat{\mu}_{\text{MrP}} = 0.337 \quad (\text{Post. sd} = 0.039)$

[10] Based on Kastellec, Lax, and Phillips (2010), see also Lax and Phillips (2009).

Covariate balance for primary effects

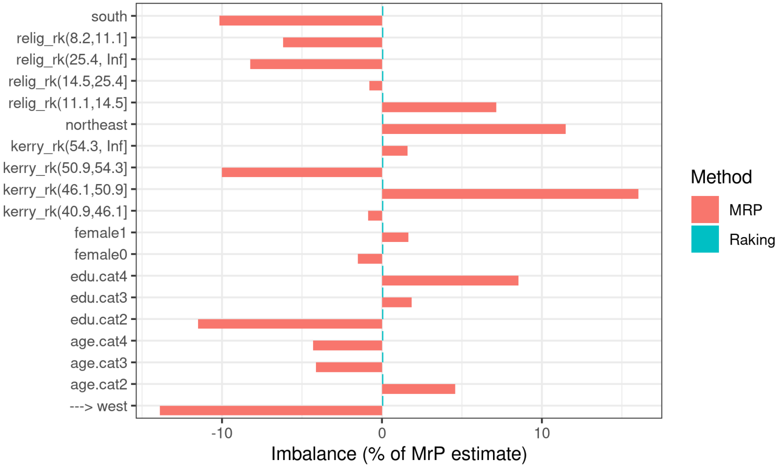

Figure 4: Imbalance plot for primary effects in the Gay Marriage dataset

Covariate balance for interaction effects

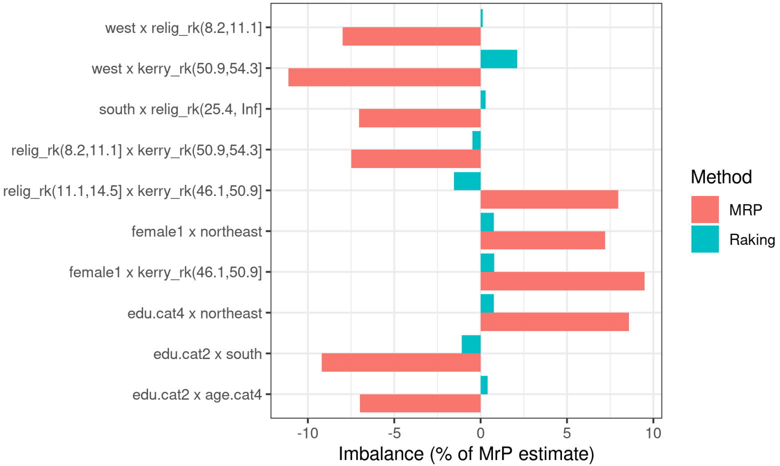

Figure 5: Imbalance plot for select interaction effects in the Gay Marriage dataset

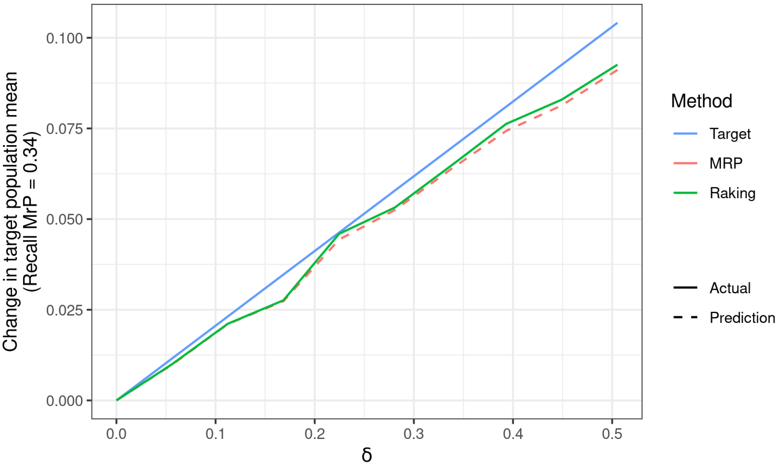

Figure 6: Predictions on binary data for the Gay Marriage dataset

Predictions and actual MCMC results

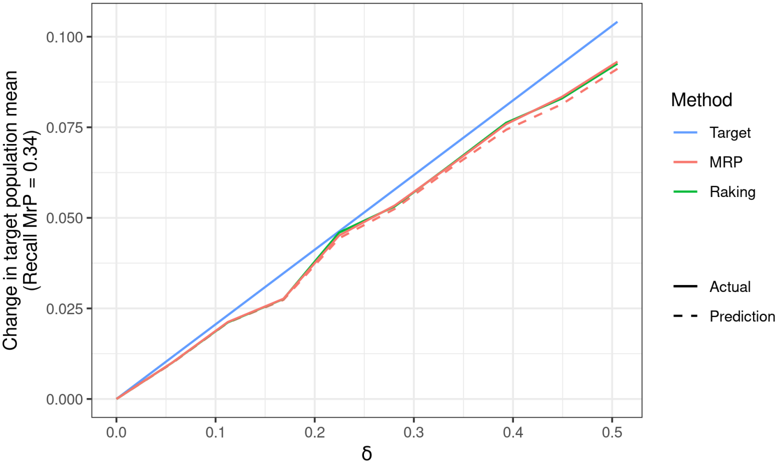

Figure 7: Predictions and refit on binary data for the Gay Marriage dataset

Running ten MCMC refits: 11 hours   Computing approximate weights: 23 seconds